Point detector scoring in GEANT4

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Introduction

PROBLEM:

- We want to determine the flux of particles at an small detector, but only very few particles reach it, so we need huge statistics

SOLUTION:

- Send a few particles and at each interaction (including at creation) compute
  - the probability that a particle of that type is produced (or the original deviated) in the direction that it would reach the detector
  - the probability that the produced particle pointing to the detector reaches it with no interaction
    - For charged particles compute the average energy loss
- Multiply these two probabilities and add the result to the scoring

Theoretical formulae

Flux of particles at a given point:

$p(\mu,\varphi)d\Omega$ = probability of a particle being scattered or born in solid angle around (μ,φ)   (μ = cos(θ))

- If there is azimutal symmetry: $p(\mu,\varphi) = p(\mu)/2\pi$
- If dA is an area normal to particle line of flight: $d\Omega = dA/R^2$

$e^{-\lambda}$ = probability that it reaches the detector with no further collisions

λ = total number of mean free paths integrated over trajectory

⇨ Flux (particle/unit area):

$$\Phi(r,E,t,\mu) = p(\mu)e^{-\lambda}/2\pi R^2$$

❖ NOTE: The **1/R²** can give a singularity when the interaction is very close to detector

– Define an **exclusion sphere** R < R_0 and the flux is the average flux uniformly distributed in the volume (assuming there is only 1 material)

$$\Phi(R<R_0) = \frac{p(\mu)(1-e^{-R_0\Sigma_t})}{2\pi R_0^3 \Sigma_t/3}$$

Σ_t = total macroscopic cross section

Theoretical formulae (2)

Small detector:

- If detector is not point-like, but is is small, above method is still valid

  For each interaction, use a random point in the detector

- This is indeed the way it is implemented in GEANT4:
  - A very small detector (e.g. ~ 10 microns) should be created and selected by the user as detector
  - This avoids the CPU penalty of parallel navigation

Implemention in GEANT4: ANGLE distribution

- Each time **a primary or secondary particle is created**, and each time it **suffers an interaction that deviates it**, the **probability** of being **created or deviated towards the detector** is computed.

ANGLE PROBABILITY DISTRIBUTION:

❑ **Particle creation:**

- Use your PrimaryGenerationAction distribution
- NOTE: probably your source is far from detector, so that the probability of reaching it is negligible, and you can skip this caset

❑ **Particle interaction:**

☹ It is not possible to get the emission angle probability for each interaction

☹ There is no simple formula or table!

Implemention in GEANT4: ANGLE distribution (2)

SOLUTION: generate N particles at different energies and build histograms with the emission angle for each interaction type in each material

- It can also be used for particle creation probabilities

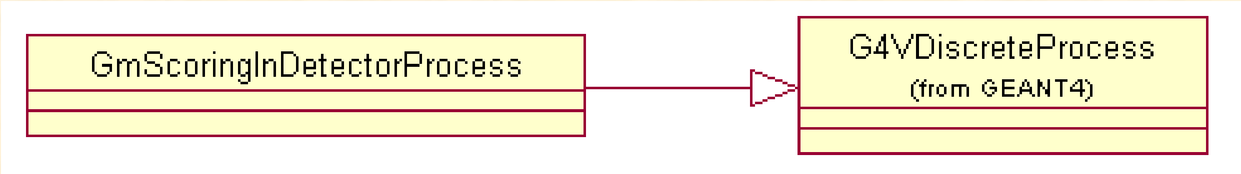
- An independent job to create all the tables
  - A table for each particle type, each material and each interaction type

- **GmAngleTablesAction:**
  - Create a world of each of the setup materials
  - Send N particles of each energy
  - When an interaction happens
    - Store angle of resulting particles w.r.t. original
    - Stop particle
  - Save histograms in ROOT format (could be ASCII files)

Implemention in GEANT4: number of mean free paths

We need to know the **number of mean free paths** of the particle from the source or interaction point until the detector (without interacting)

- Create a geantino and track it until detector:



GmScoringInDetectorProcess::PostStepDoIt

- If it is an interaction that deviated the particle or created a secondary particle of the desired type, it creates a G4Geantino
  - **Position** = interaction point
  - **Energy** = the original particle energy
  - **Direction** = towards detector point
  - **Weight** = probability of emission at angle towards the detector

Implemention in GEANT4: number of mean free paths (2)

- At each geantino step, get the weight = exp(-Number of mean free paths)

GmScoringInDetectorAction::SteppingAction

  - Number of mean free paths = step length / mean free path
    - Add microscopic cross sections (=inverse of mean free path) for each process

    process->GetMeanFreePath(myParticleTrack,0,G4ForceCondition*)

    - Needs to create myParticleTrack with current energy
  - If in exclusion sphere, compute weight as average in sphere

- If geantino reaches the detector, add its weight to the scoring
  - Energy bins are defined by reading an ASCII file provided by the user

Example

- Point detector scoring for neutrons
  - EU CONRAD (Coordinated Network for Radiation Dosimetry) WP 3 benchmark

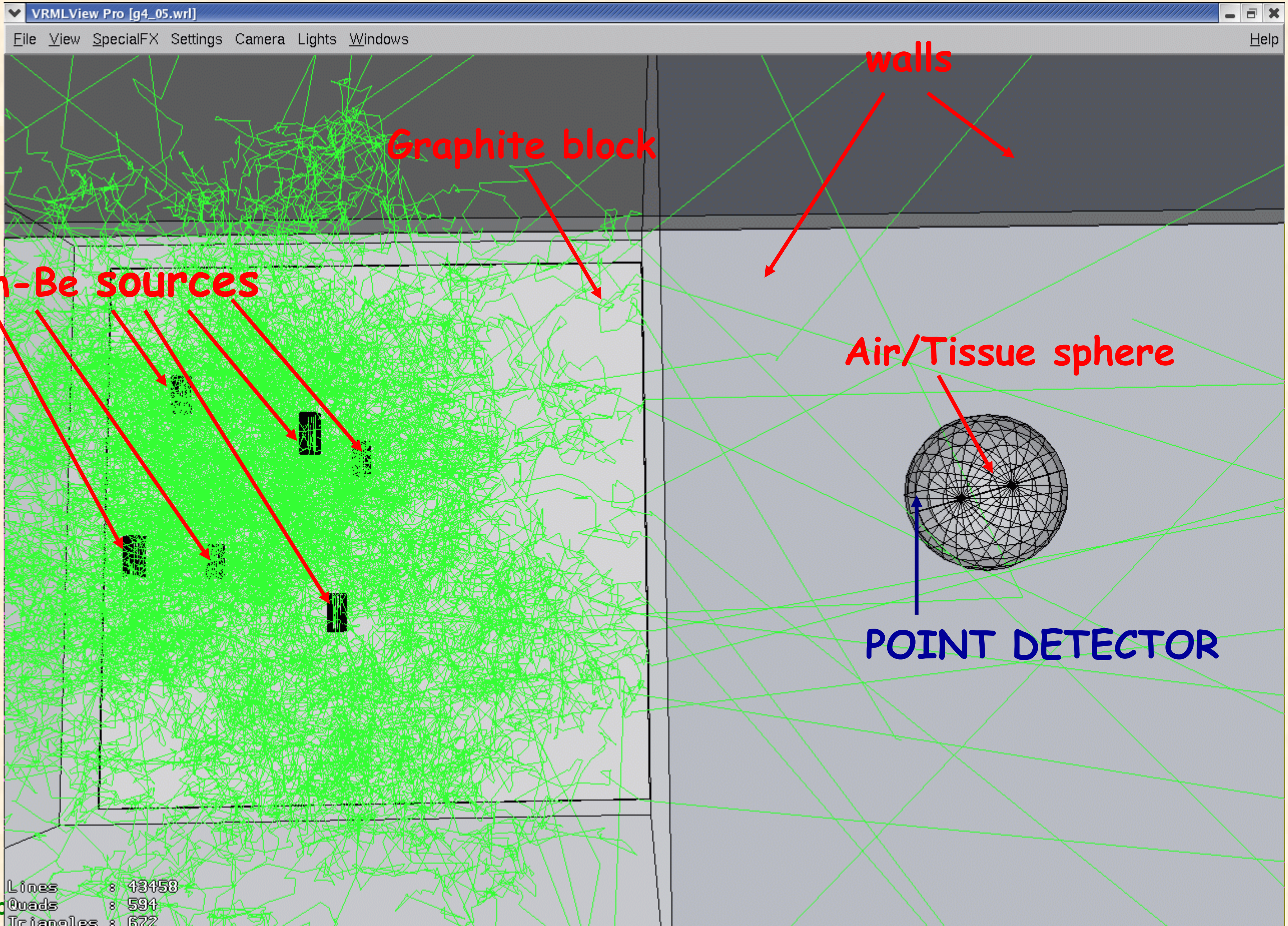
SETUP:

- 6 Am241-Be sources of neutrons of energies 0.1-11 MeV
- Inside a 1.5m length concrete block
- Flux at 1.25 m in air and in a tissue sphere

✓ Compare results with MCNP

- 100 M events in MCNP: **0.06 seconds/event**
- 20 M events in GEANT4: **0.6 seconds/event** (**0.2 GEANT4**, **0.4 scoring**)
- NOTE: 100M events are not enough in the tissue sphere (see statistical tests)

Example


VRMLView Pro [g4_05.wrl]
File View SpecialFX Settings Camera Lights Windows Help
walls
Graphite block
Am-Be sources
Air/Tissue sphere
POINT DETECTOR
Lines : 43458
Quads : 594
Triangles : 672

Example: output

N tables of sum of weights of particles reaching the point detector:

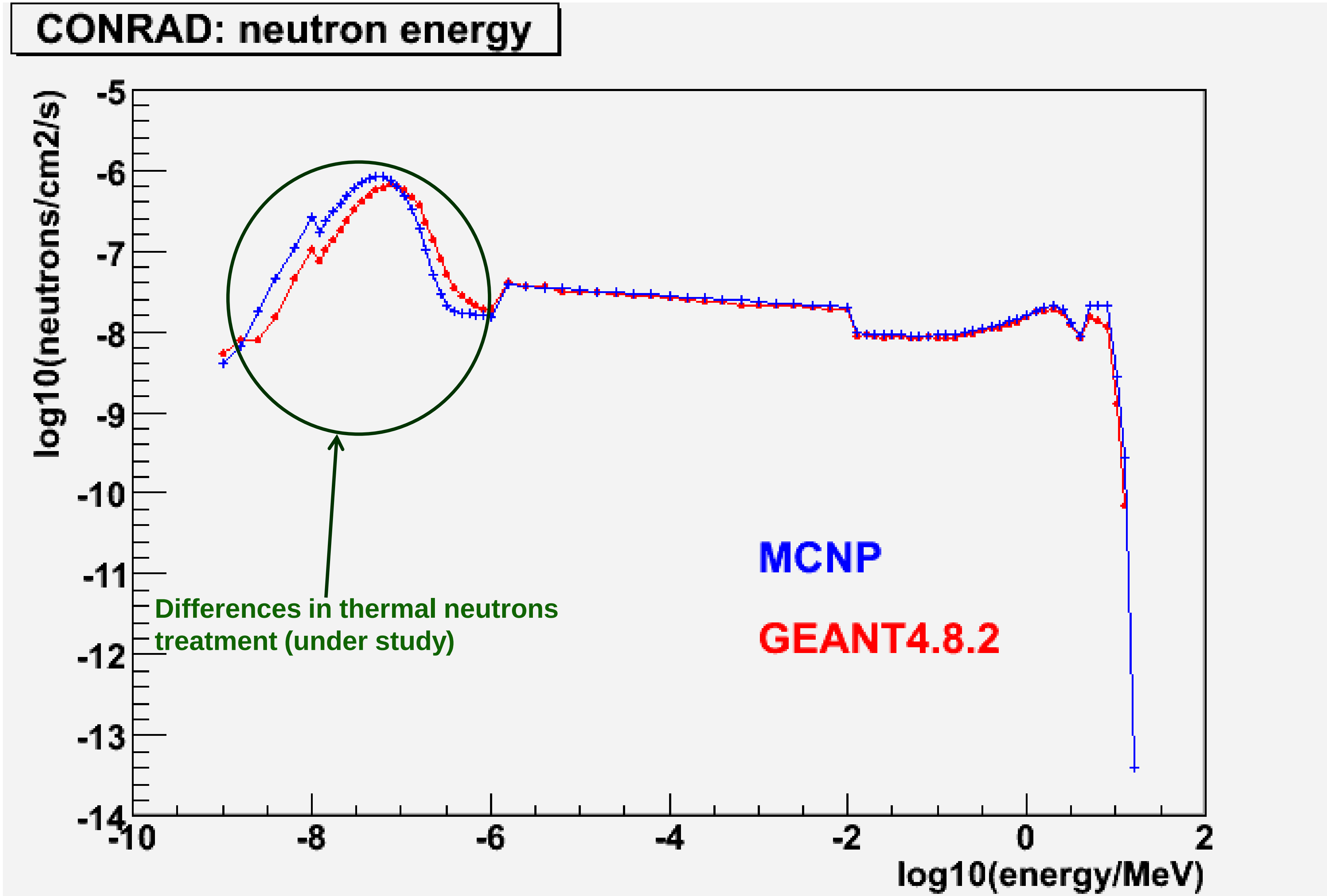
- One table with all particles
- One table depending on the volume where interaction occurred
- Other tables defined by the user

```
%%%%%% TALLY IN POINT DETECTOR FOR set ALL at (1250,0,0)
ALL ENERGY: 9.9999997e-10 FLUX= 2.1310454e-05 +- 1.2928428e-09  N 67 Fwei2 4.1868533e-11 Fwei3 1.1706198e-16 Fwei4 3.7855976e-22
ALL ENERGY: 1.585e-09 FLUX= 2.5113599e-05 +- 1.7089605e-09  N 82 Fwei2 7.3125186e-11 Fwei3 3.5589648e-16 Fwei4 2.0648728e-21
ALL ENERGY: 2.5119999e-09 FLUX= 0.00010455708 +- 1.6643464e-08  N 177 Fwei2 6.9259238e-09 Fwei3 5.6822955e-13 Fwei4 4.7024096e-1
ALL ENERGY: 3.981e-09 FLUX= 0.00026958511 +- 4.5015909e-08  N 789 Fwei2 5.0665204e-08 Fwei3 1.1167403e-11 Fwei4 2.4909888e-15
….
ENERGY: TOTAL = 0.036487325 +- 2.4458457e-07  N 328703
%%%%%% TALLY IN POINT DETECTOR FOR set grafiteBlock at (1250,-8.5722445e-15,0)
grafiteBlock ENERGY: 9.9999997e-10 FLUX= 1.5578507e-05 +- 1.0176278e-09  N 27 Fwei2 2.593252e-11 Fwei3 6.4104578e-17 Fwei4 1.926
grafiteBlock ENERGY: 1.585e-09 FLUX= 1.598629e-05 +- 1.0448814e-09  N 26 Fwei2 2.7340082e-11 Fwei3 6.9046248e-17 Fwei4 2.021163e
grafiteBlock ENERGY: 2.5119999e-09 FLUX= 0.00010087196 +- 1.6639529e-08  N 116 Fwei2 6.922499e-09 Fwei3 5.6822472e-13 Fwei4 4.70
grafiteBlock ENERGY: 3.981e-09 FLUX= 0.00026128898 +- 4.5007988e-08  N 661 Fwei2 5.0646502e-08 Fwei3 1.1167334e-11 Fwei4 2.49098
…
```

Each line contains:

- **set_name**
- "ENERGY" **energy_value**
- "FLUX=" **flux_value**
- "+-" **flux_error**
- "N" **Number_of_particles**
- "Fwei2" **flux_second_momentum**
- "Fwei3" **flux_third_momentum**
- "Fwei4" **flux_fourth_momentum**

Example


CONRAD: neutron energy
log10(neutrons/cm2/s)
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-10
-8
-6
-4
-2
0
2
log10(energy/MeV)
Differences in thermal neutrons
treatment (under study)
MCNP
GEANT4.8.2

Statistical tests

- Often the statistics are not enough for the problem, and it is not easy to realize of it
- MCNP makes 10 detailed statistical tests of the results of the point scoring detector:

MEAN:

1) A nonmonotonic behavior (no up or down trend) in the estimated mean as a function of the number histories N for the last half of the problem;

R = $S_{\bar{x}}$ / $\bar{x}$ (relative error):

2) An acceptable magnitude of the estimated R of the estimated mean (< 0.05 for a point detector tally)

3) A monotonically decreasing R as a function of the number histories N for the last half of the problem

4) a 1 / N decrease in the R as a function of N for the last half of the problem

Statistical tests

VOV: Variance of the Variance

5) The magnitude of the estimated VOV should be less than 0.10
6) A monotonically decreasing VOV as a function of N for the last half of the problem
7) a 1/N decrease in the VOV as a function of N for the last half of the problem

Figure Of Merit = 1 / R^2T (T= time)

8) A statistically constant value of the FOM as a function of N for the last half of the problem
9) A nonmonotonic behavior in the FOM as a function of N for the last half of the problem

f(x) = History score probability density function

10) The SLOPE of the 25 to 201 largest positive (negative with a negative DBCN(16) card) history scores x should be greater than 3.0, so that the second moment will exist if the SLOPE is extrapolated to infinity

Summary

- ✓ Point detector scoring has been implemented in GEANT4
  - ➢ Calculate at each interaction point, the probability that it would reach the point detector without further interacting

- ✓ An example done for neutrons
  - ❑ Easy to extend it for other particles
  - ❑ Uses several of the GAMOS framework utilities, but not difficult to do it GAMOS- independent

- ✓ Very good agreement with MCNP point detector scoring

- ➢ **Statistical tests not yet implemented**